

Radiation interception and modelling as an alternative to destructive samples in crop growth measurements

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Summary

Growth analysis presently uses destructive samples to detect temporal variations in biomass. The destructive nature of the measurements, their cost, and statistical considerations limit the application of growth studies in many domains of crop science. In contrast radiation interception data are cheap and easy to obtain without destruction of experimental material. Biomass may be modelled as the product of cumulative radiation intercepted by the crop [ΣI] and a radiation use efficiency coefficient [e]. Therefore, in theory, an alternative to destructive samples is provided by measurement of I at intervals during growth and e . The success of this approach depends on the validity of the value of e and its constancy through time. With measurement of I at intervals the mean radiation use efficiency [\bar{e}] can be estimated from the seasonal ΣI and the final harvest data. The \bar{e} can then be used with the time series data for ΣI to estimate the biomass for that plot for any date. To test this approach model-derived biomass data were compared with data from destructive samples at seven dates for six groundnut germplasm lines grown in water limiting and fully irrigated conditions. The model-derived data was consistently less than destructively obtained data when the plants were small. This bias was an artifact of the interception measurement technique used not being accurate for small plants. Once plants were tall enough for fractional interception to be measured without substantial error, the nondestructive method effectively described the growth of the well-watered crops. For the drought treatments, it was less effective. However, by dealing with the phases of growth separately, good correlation between the two methods was achieved. An important assumption in the method is that the final harvest biomass is a realistic reflection of the preceding growth, since the model method forces the estimates of growth to that point. In one germplasm line this assumption was not valid and the model-based method did not match the sampled biomass data.

Key words: Nondestructive growth measurement, light interception, *Arachis hypogaea*, groundnuts, growth analysis

Introduction

Measurement of the changes in mass of plant structures across time is usual in crop physiology. Traditional growth analysis involves a time series of observations of the mass of

various plant structures (stem, leaf, fruit etc.) and the area of the leaves, and is usually very labour-intensive. Leaf area is a traditional measurement, with a very high labour cost, usually collected to provide implicit information about light capture. The mass of plant components is used to estimate their growth rates, and the variation in partitioning of assimilates between structures. The cost of processing destructive samples limits both the number of treatments that can be considered in most research efforts, and the precision with which these can be estimated (small samples). Traditional growth analysis has several other limitations, most particularly the fact that it destroys some part of the crop at various times and therefore increases the problems of statistical variability and interpretation of results, and increases the plot size needed.

Since growth analysis is such a costly procedure, methods of obtaining comparable data without the large investment of labour would be highly desirable and lead to greater returns from the money invested in research. Similarly the value of many agricultural experiments could be greatly enhanced if the data about the growth, and the partitioning of this growth were possible. This information would allow better interpretation of the results within the context of processes and resource exploitation. For crops grown without major stresses reliable comparative values of partitioning are possible from phenological observations and final harvest data (Williams, 1992). Since this method (Williams, 1992) assumes a constant growth rate between emergence and final harvest, it is less reliable when substantial variations in the growth occur during different phases of the crop's life. This circumstance exists when drought or disease occurs, and realistic determination of the partitioning of growth to fruit then demands an estimate of biomass at both the start of reproductive growth and at maturity.

Primary productivity by crops may be modelled as the product of resource capture and resource use efficiency (Monteith, 1977). For radiation, this may be expressed as:

$$M = \Sigma I \cdot e \quad [1]$$

where M = mass, ΣI = cumulative light interception, and e is a coefficient expressing the radiation use efficiency. Monteith (1977) suggested that this model would be robust because substantial variations in other resources needed for growth manifest themselves mostly in variations in leaf area and I . This model has been well validated for many crops, including groundnuts (Matthews, Harris, Williams & Nageswara Rao, 1988), and it has been confirmed that e is a relatively conservative value. For groundnut, variations in water supply alter light interception through changes in leaf area, or leaf-angle in the short term (Matthews *et al.*, 1988) rather than through large changes in the efficiency term (Azam Ali, Simmonds, Rao & Williams, 1989). However, in simulating crop growth, radiation use efficiency has not been constant enough to allow the exploitation of a single resource capture model. Successful simulation modelling based on the resource capture approach has had to use multiple models, the choice of which is governed by the most limiting resource, to cater for variations in the resource use efficiency term (Campbell & Stockle, 1993).

Measurements of fractional light interception (f) are non-destructive, simple and inexpensive to make. Most commonly f is measured by placing a linear radiation sensor under the canopy and estimating the radiation intercepted by difference from the above-canopy incident radiation value. However, f may be measured in several ways (Gallo, Daughtry & Weigand, 1993; Nageswara Rao, Williams, Rao & Wadia, 1992), and the best method to measure f can be expected to vary with species and phenology. Gallo *et al.* (1993) showed that when senescent material was present, the reflectance methods were more reliable than direct interception methods.

Measuring the f at intervals through the crops life (to calculate ΣI) and biomass at final harvest allows an average radiation use efficiency [\bar{e}] for a particular plot to be estimated. In principle these data (ΣI and \bar{e}) can then be used to estimate the biomass at any stage of growth

for which ΣI is known. The objective of the experiment described in this paper was to test the use of radiation interception measurements through time combined with a measured plot value of $\bar{\epsilon}$ as an alternative to destructive samples for growth description.

Materials and Methods

Experimental treatments and management

The experiment was conducted at ICRISAT's Asian Center, situated near Hyderabad in India, between 11 December 1991 and 17 April 1992. Six groundnut (*Arachis hypogaea* L.) lines (cultivars and breeding lines) with differing attributes were used. These were grown in factorial combination with full irrigation until maturity, or without irrigation from 77 days after sowing (DAS). Plots were arranged in a split plot design with irrigation as the main plot treatment, and there were four replications. Seeds were sown 10 cm apart in four rows at 30 cm intervals on broad beds 1.5 m wide. The plots were weeded by hand, and insects were controlled when scouting showed significant presence of pests. Rogor[®] was used against thrips and jassids (sucking pests) at 36, 51 and 112 DAS.

Phenology, growth analysis, and final harvest

Crop samples (1 m²) of shoot and fruit were taken from each plot at 33, 49, 64, 80, 96, 111, 127 DAS. Plants were separated into reproductive and vegetative parts and these were oven-dried at 80°C to constant weight. Leaf area was not measured.

All the treatments were grown until 129 DAS regardless of maturity. At this time an area of 5.25 m² was harvested and the harvested material separated into pods and vegetation, air dried and weighed. Sub-samples were used to determine the moisture content of the larger samples, which were then corrected to 0% moisture.

Radiation interception measurements

Measurements of the fractional interception were made on the same day as the growth samples using a LICOR line quantum meter. This equipment was used throughout growth, despite the recognised problems of measuring f when plants are small and when the height of the instrument makes it impossible to place completely below the canopy. Measurements were made above and below the canopy in three locations in each plot, between 11.00 and 13.00 h.

Data manipulation

Standard Genstat 5.2 (Numerical Algorithms Group Ltd) statistical practices were used for analysis and data manipulation. The f_{nj} for plot n was estimated for day j (where $j = 0$ at emergence and $j = 129$ final harvest) using the interpolation function of Genstat and the values of f on the sample dates. The daily radiation measured at the meteorological station was multiplied by f_{nj} to estimate I_{nj} , and accumulated (ΣI_{nj}) between emergence and final harvest, with I_{nj} retained for the days on which f was measured and growth samples done.

All shoot masses were weighted for the higher energy content of the pods using the method of Duncan, McCloud, McGraw & Boote (1978) using equation [2] to ensure that the data was not confounded by the ratio of pods to other plant components (i.e. that it had a consistent energy content).

$$A = V + (1.65R) \quad [2]$$

Table 1. *Effects of germplasm line and irrigation on energy adjusted biomass, cumulative light interception and radiation use efficiency at final harvest (129 days after sowing)*

Germplasm	Energy adjusted biomass g m ²		Cumulative light interception ΣMJ m ⁻²		Light use efficiency g MJ ⁻¹	
	Irrigated	Drought	Irrigated	Drought	Irrigated	Drought
Chico	288	157	584	720	0.51	0.22
TMV2	785	386	1193	954	0.66	0.41
TMV2NLM	776	408	1042	696	0.74	0.63
ICGV86031	921	435	1208	804	0.76	0.56
ICGV86635	838	376	1161	867	0.72	0.44
ICGV86707	782	391	1058	601	0.74	0.68
Mean	732	359	1041	774	0.69	0.49
SE (30 df)	32.5		66.4		0.047	

where A = energy adjusted harvest mass, V = vegetative mass, and R = pod mass. The radiation use efficiency of each plot was computed using equation [3]:

$$e_{nj} = A_{nj} \div \Sigma I_{nj} \quad [3]$$

where e_{nj} = radiation use efficiency (g MJ⁻¹) for plot n on day j . The seasonal mean radiation use efficiency (\bar{e}_n) was calculated from the large plot final harvest data and ΣI_{nj} (where $j = 129$). An energy adjusted biomass for each plot was estimated for the days of growth analysis as the product of \bar{e}_n and ΣI_{nj} ($j = 33, 49, 64, 80, 96, 111, 127$).

The data for ΣI_{nj} , A_{nj} and e_{nj} were subjected to analysis of variance for each date using conventional statistical approaches. Firstly, for individual sample dates, regression-based analysis of variance using Genstat's REML procedure was used to learn the distribution of the total sums of squares between the estimated biomass ($\Sigma I \bar{e}$), residual effects of ΣI , and the experimental treatments. Then regression was used to examine the relationship between sample data and model derived estimates across all the sample dates.

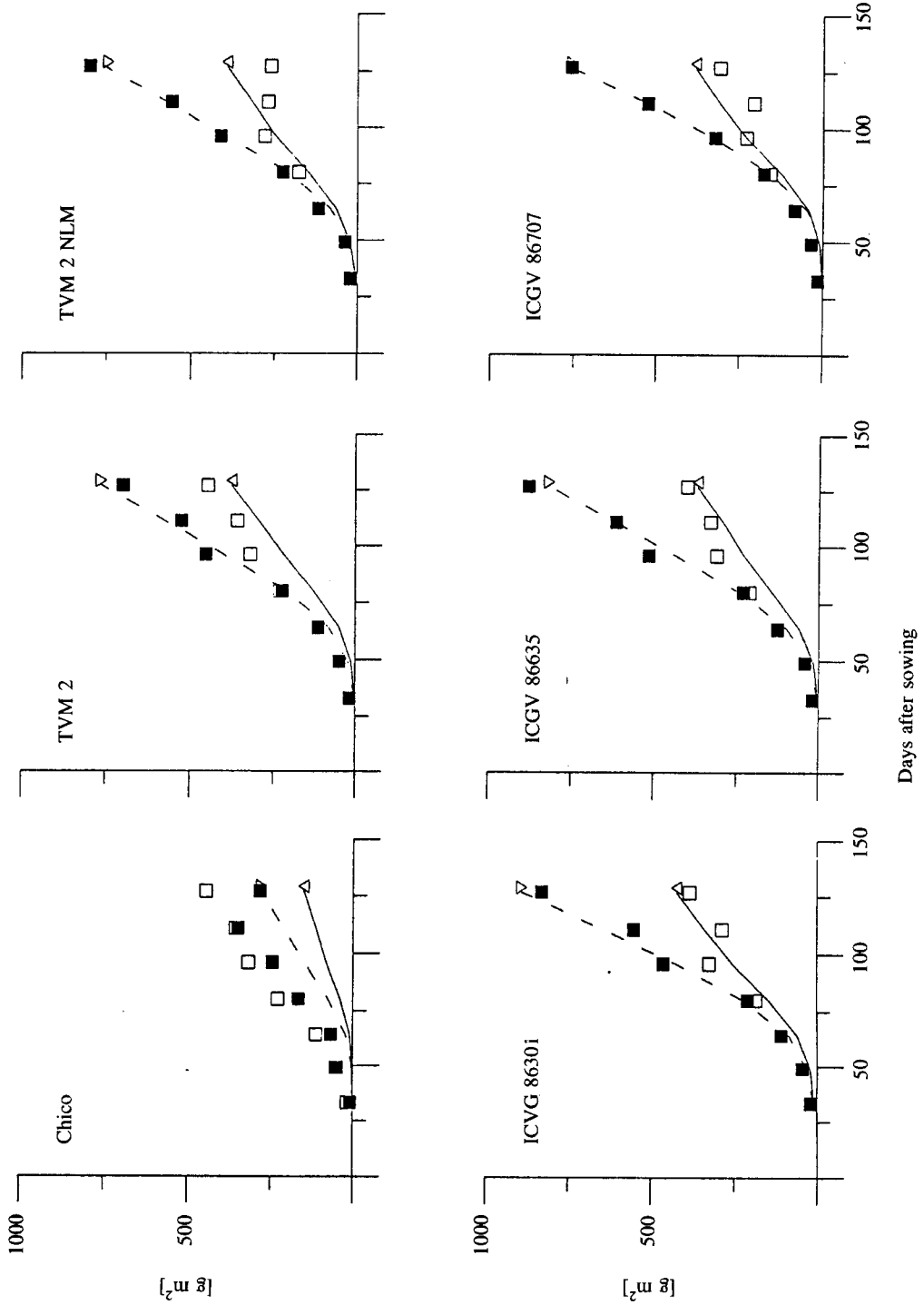
Results

Variation in productivity, light interception and radiation use efficiency

The final harvest dry mass for the different treatments is presented in Table 1. The germplasm lines produced different amounts of energy adjusted shoot mass (288 to 921 g m⁻² in well watered conditions), and drought decreased growth from 732 g m⁻² to 359 g m⁻² (averaged across all germplasm lines). Cumulative radiation interception varied in a similar fashion for germplasm lines (584 – 1208 MJ m⁻² between germplasm lines), while drought decreased radiation interception from 1041 to 774 MJ m⁻². The resulting estimates of \bar{e} varied from 0.51 to 0.76 g MJ⁻¹ m⁻² between germplasm lines in well watered conditions and these decreased from an average of 0.69 to 0.49 g MJ⁻¹ m⁻² in response to the drought treatment.

The changes with time in shoot biomass as estimated from the light interception measurements and the model, and as measured by destructive sampling are presented in Fig. 1.

Fig. 1. Changes in crop dry matter for six groundnut germplasm lines grown under droughted (□) and irrigated (■) conditions at Patancheru, India 1992. Corresponding final harvest data are indicated by Δ and ∇. The lines join the biomass estimated for droughted (—) and irrigated (- - -) treatments by the model combining radiation interception and mean radiation use efficiency.



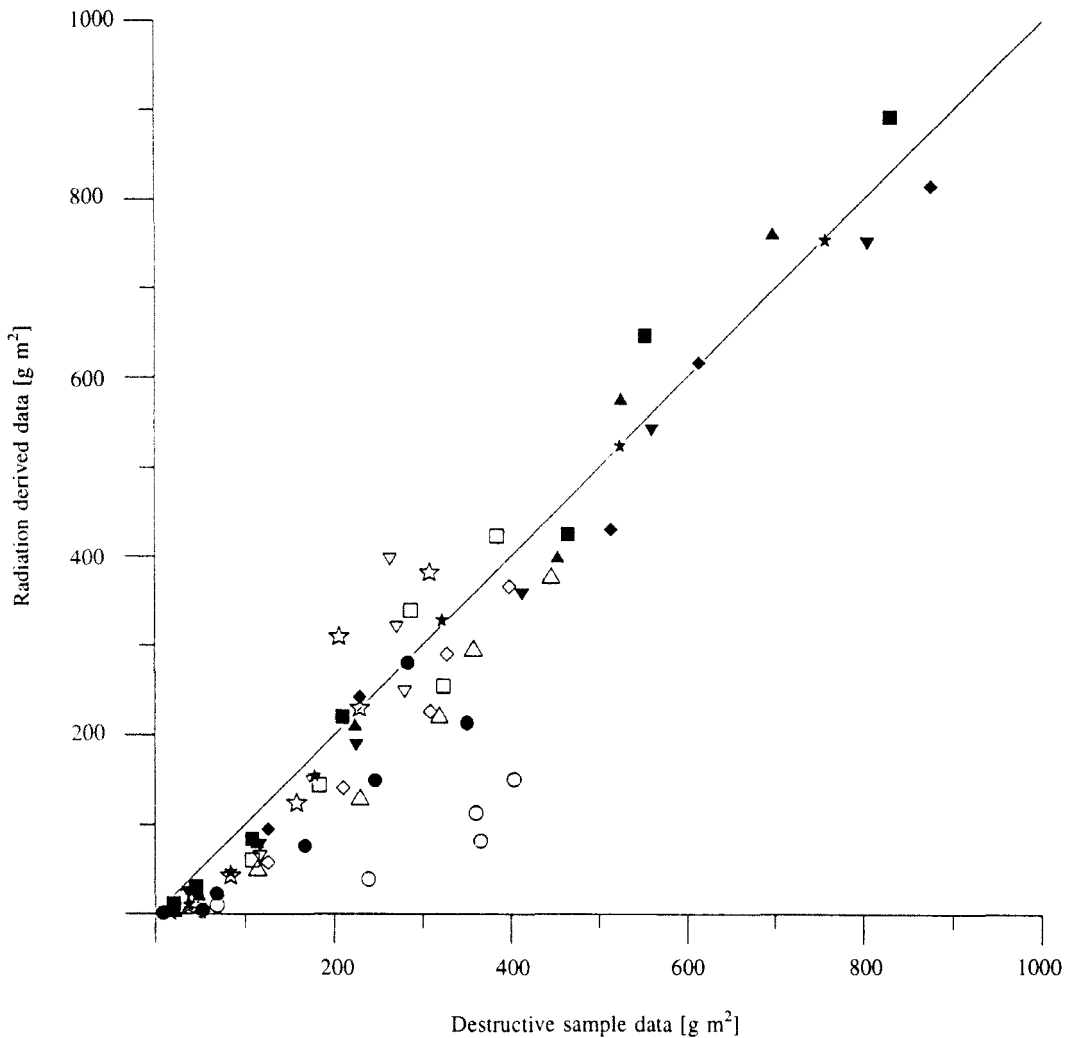


Fig. 2. Calculated and measured values of crop dry weight at seven sampling dates for six germplasm lines grown under two irrigation regimes at Patancheru, India. The 1:1 line is not fitted. Open symbols denote droughted treatments, filled symbols denote irrigated treatments. (○ Chico, △ TMV2, ▽ TMVNLM, □ ICGV 863031, ◇ ICGV 86635, ☆ ICGV 86707).

The sampled time series data projected to the final harvest data reasonably well for most treatments, excepting those involving Chico. The time series data showed that the drought treatment had little impact on the growth of Chico, however, the growth sample at 127 DAS (403 g m^{-2}) and final harvest (157 g m^{-2} at 129 DAS) differed substantially.

The e_j data showed that during the early stages of crop growth there was considerable overestimation of radiation use efficiency relative to \bar{e} , a result to be expected with the limitations of the equipment used to measure f . At each sample date the analysis of variance showed that the model accounted for most of the variance in the sample data and the treatments, while remaining statistically significant, were usually responsible for between only 3% and 7% of the total sums of squares. At each sample date the ΣI_j was a significant factor in the analysis of variance despite the inclusion of the predicted biomass ($\Sigma I_j \bar{e}$).

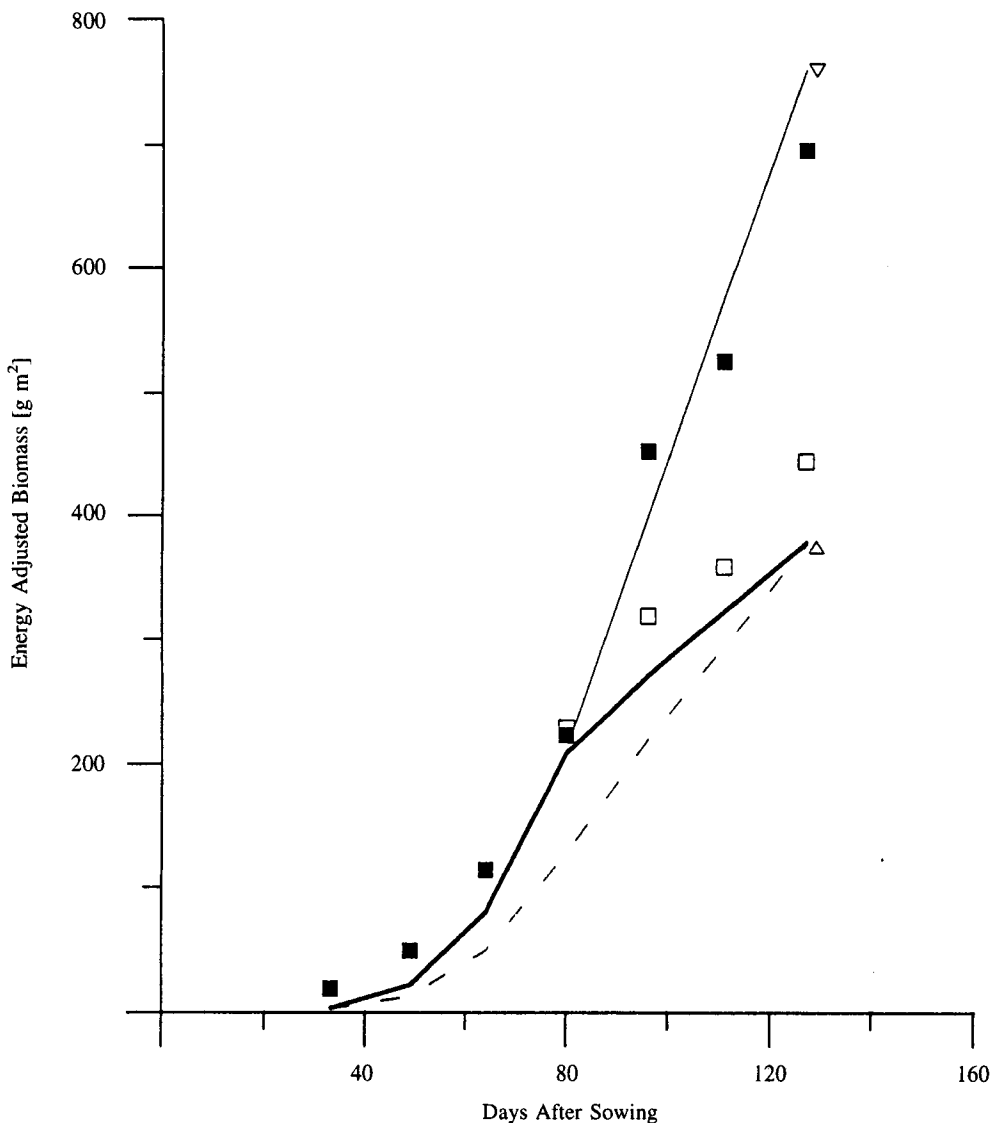


Fig. 3. Changes in crop dry matter for TMV2 grown under droughted (\square) and irrigated (\blacksquare) conditions at Patancheru, India 1992. Corresponding final harvest data are indicated by \triangle and ∇ . The fitted lines (---) and (—) indicate the corresponding biomass estimated by the model combining radiation interception and mean radiation use efficiency. The line (—) indicates the consequences of using the radiation use efficiency term for the irrigated treatment to estimate the mass at the start of the drought and a radiation efficiency term specific to the droughted phase.

Modelled growth data

Regression analysis between modelled and measured data was done excluding the data for Chico because of the obvious problems of measuring f on this germplasm line, and because of the discrepancy between the final data and the times series projection described above. The calculated $A_{j=129}$ is also the final harvest data from the large plots because of the method involved, and is the data typically available from most agronomic and breeding experiments.

This endpoint should be the most accurate representation of growth because of the larger plot size involved.

For the early sample dates there was a systematic difference between the sampled and estimated shoot mass. The calculated values were usually less than the destructive-sample data during early growth, later the values for the well-watered crops agreed well the sampled data, but those for droughted crops generally underestimated shoot mass as shown by Fig. 1. A plot comparing the calculated and measured values (Fig. 2) shows how well the model data related to measured shoot weights. It shows the extent of underestimation due to inaccuracies on measuring f on small plants, and that due to using the \bar{e} over both light and water limiting growth phases; and the lower values for Chico in the drought treatment resulting from the low I measurements.

Discussion

The absolute values of e were less than generally reported for crops. The reason for this is not clear, but while the values are used only to redistribute growth within the context of their parent data set the problem is not relevant to the application of the model to nondestructive growth estimation.

Where the plants were tall enough for the measurement of f to be accurate, and where the plants were well watered throughout the experiment, the model-based description of growth was successful for five of the lines. However, as suggested possible by the simulation modelling experience (Campbell & Stockle, 1993) radiation based estimation was less successful at describing growth when crops suffered drought for part of their growth. This problem arises because of the use of \bar{e} which underestimated growth during the phase of light limited normal growth. However, in this particular experiment where the drought commenced at a defined stage and where a control treatment existed this problem could be overcome by using the \bar{e} from well-watered treatments during the predrought phase to estimate the biomass at the start of the water stress period. Then, by estimating the growth during the stress by difference from the final harvest data a second e appropriate for the droughted phase can be calculated and used to estimate the growth during the water deficit phase. The outcome of this approach is shown for one line in Fig. 3.

The estimated crop dry weights differed systematically from the measured values in the early stages of growth. This was because the line quantum sensor did not accurately measure the fractional interception since a large fraction of leaves were below the top of the sensor, as a consequence values of e were higher during this phase than the \bar{e} . Measurements of f by short plants would be better done by reflectance ratios (Gallo *et al.*, 1993; Nageswara Rao *et al.*, 1992), or by photographic analysis. With small groundnut plants, simple measurement of plant diameters may suffice since interception within the bounds of the canopy is usually high (>90%, S N Azam Ali, personal communication). However, even with these limitations to the accuracy of the method, the predicted biomass was very well correlated with measured biomass ($R^2 = 0.96$ without Chico, $R^2 = 0.91$ with Chico).

Several problems were encountered in the data of, and the modelling of growth by Chico (Table 1 and Fig. 1). First, the measurement of radiation was a major source of error because of the small stature of this cultivar. Secondly, Chico normally matures much earlier than the other germplasm lines and it is clear from comparison between the growth data and final harvest that considerable quantities of plant material were lost prior to, or at, the bulk harvest so the \bar{e} was underestimated. The impacts of lost material at final harvest will remain a potential hazard to radiation based estimation of growth using \bar{e} and accuracy should be improved by paying attention to recording the extent of losses such as defoliation. When it is

known that there was a loss of material at harvest one could, with caution, reconstruct the growth using either a general value for \bar{e} , or the experimental mean radiation use efficiency. Where defoliation has been quantified, the biomass can be adjusted for this missing material (Williams & Saxena, 1991). That Chico did not appear to be affected by the drought treatment during growth (only at the final harvest) is possible given the small canopy established.

Traditional growth analysis requires data for biomass, distribution of mass between structures, and leaf area. The method proposed here, combined with other low-cost non-destructive techniques, has the potential to replace much of the expensive growth measurement presently used in crop science. It can also add the benefits of growth description to many experiments where costs or the destructive sampling requirement prohibit traditional growth analysis. However, before using the method one needs to consider the limitations and decide how serious these are relative to the benefits to be gained by either lower costs, or additional information where it is presently not possible.

The first problem detected in this data set was the accuracy of measuring f by small plants. Reflectance ratio techniques provide a ready solution to this problem. One could also use destructive growth samples to quantify early growth for which direct measurements of f are prone to error; then as the canopy develops and measurements of f become more reliable a switch to the less costly radiation method could be cost effective. The second problem stemmed from variation in the radiation use efficiency in the event of different resources being the limiting factor over different phases of growth. In experiments with a control treatment a feasible solution to this problem has been demonstrated. Another alternative would be to combine strategically timed destructive samples to establish e values appropriate for the intervals. The proposed method does not provide direct data on leaf area, but for many circumstances leaf area is measured to indicate light interception which in this case is measured directly.

An important possible application is to enhance the information obtained from trials where either the numbers of treatments, or the locations of the trials make growth analysis impossible. With better description of the growth and phenological observation more reliable estimation of partitioning to reproductive structures should be achieved. With plant breeding the ability to describe growth and partitioning more reliably has theoretical significance to the breeders' ability to select for yield with greater confidence than at present. This application could reduce substantially the cost of varietal development.

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